STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

W. H. PETERS
E. W. PETTY

ARMOUR INSTITUTE OF TECHNOLOGY

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Peters, William H.
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A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

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WILLIAM. H. PETERS

EDWIN W. PETTY

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INTRODUCTION.

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

With the constantly increasing nimber of long distance alternating current transmission lines for both lighting and power it has become necessary for manufacturers to turn their attention towards the developing of the alternating current motor. During the last few years the alternating current series motor has been developed to a high degree of perfection. A large starting torque and a wide variation of speed, which are the characteristics of the direct current series motor, are also characteristic of the alternating current series motor. It is therefore used for traction, and for driving machinery which requires a large starting torque and a wide speed variation.

In order to appreciate the importance of t the alternating current motor it may be well to point out a few advantages of the alternating current system over the direct current system.

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

The advantages obtained from the use of alternating current for traction lies in the economy of transmission rather than to any improvement of the alternating current series motor. Where power is to be transmitted for a considerable distance a high voltage is desirable. When alternating current is used this high voltage may be stepped down by means of transformers where the power is to be utilized. In the case of electric railways the transformer may be carried upon the car and the voltage stepped down to any desirable value.

In the case of long distance electric roads transformer stations can be used for stepping down from a very high voltage to a desirable trolley voltage. In these transformer stations there is no rotating machinery, and hence, the maintainance and operating expenses are small.

On the other hand, where direct current motors are used for traction, it is necessary to use either direct current transmission ar to transmit alternating current to rotary converter substations, from which the line is supplied with direct current. In case the direct current transmission is used the trolley voltage and the voltage at which the motors are operated is the same. Since the limiting voltage on which a direct current motor will operate satisfactorily is about six hundred volts, this will also be the voltage at which the power is transmitted, which is very low for any long distance transmission. In the case where rotary converter substations are used to transform the alternating current to direct current the operating expense may be considerable. The rotating machinery requires constant attention and the maintainance is increased. In the case of an accident or a short circuit on

the line the system may be put out of service for some time. Although the efficiency of the rotary converter is quite high it is not economical when operating on low load factor.

In the direct current system a variable voltage for starting and regulating the speed of the motors is obtained by connecting the m motors in series or in parallel and thus obtain two economical speeds. In order to obtain additional speed variation a rheostat is used. The capacity of the rheostat is generally small so that it may be left in the circuit for only a short time. Except momentarily, therefore, only two speeds are available for continuous running. The loss in the rheostat is also considerable, especially in starting.

In the alternating current system any desired voltage may be obtained across the motor by means of a transformer or a regulator, placed

on the car. The losses will be small in this case owing to the high efficiency of the transformer. The motor may be run at full speed or at any other speed and the power consumption at all speeds will be proportional to the energy actually expended in driving the car.

It is the object of the writers to obtain the general characteristics of the alternating current series motor by means of a series of tests and to point out the important features in the design of the motor.

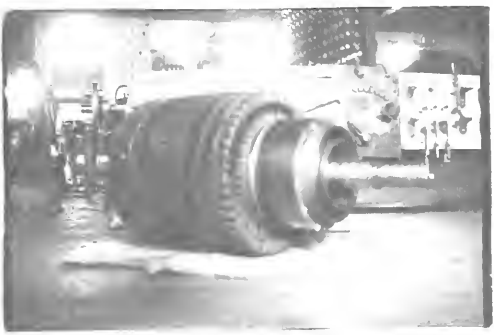
The tests on the motor were conducted in order to determine its characteristics under various conditions of load, voltage and frequency. Also to determine the losses which occur in the motor. All instruments used were carefully calibrated.

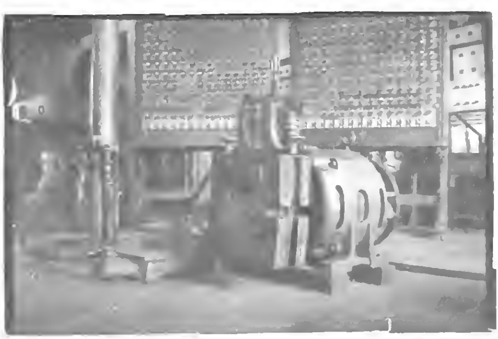
DESCRIPTION OF THE MOTOR

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

The motor tested was of the Lamme type, built by the Westinghouse Electric and Manufacturing Company. The motor is of rather an old design, being one of the first machines of this type to be placed on the market by this company. It was designed for the operation of cranes, hoists, and similar apparatus requiring intermittent service with a heavy starting torque and a wide speed variation. The motor is a four pole, one hundred volt, sixty cycle machine rated at ten horsepower, at one thousand revolutions per minute. The frame surrounding the motor is of the wholly enclosed type but is so designed that the working parts may be exposed without dismantling. The pole pieces are built of soft steel punchings riveted together between wrought iron plates and are secured to the frame by bolts. The compensating windings, field windings, and armature are all connected in series. The com-

pensating windings are placed in slots in the pole pieces, - there being twelve slots per pole. The resistance of the compensating winding being .0235 ohm. The field windings are form wound and have a resistance of .006 ohm. The armature is constructed as the ordinary direct current motor armature. There are one hundred forty one commutator segments and forty seven slots. In each commutator lead there is placed a resistance of german silver wire for the prevention of a large short circuit current under the brushes. The resistance of the armature was found to be .091 ohm, while the resistance of each lead was found to be .05 ohm. A starting and reversing rheostat such as is used for direct current motors was used in connection with the machine.





BRAKE TEST ON SIXTY CYCLES.

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

In order to determine the relations of speed , torque, power factor, output, and efficiency to the current input we applied a constant voltage to the machine and ran the brake teast. The motor was operated on sixty cycles and the impressed voltage kept constant at one hundred volts. The motor was operated on full load for some time before readings were taken in order to allow the temperature to become fairly constant. The load was varied by means of the prony brake from a minimum allowable load to the maximum safe load. At each variation of the load, readings were taken of the speed, current input, power input, and the pressure of the brake arm on the scales.

The impressed voltage was then allowed to vary and the current input was kept constant at ninety amperes and sixty cycles. Readings were again taken of speed, impressed voltage, power input, and pressure of the brake arm on the scales.

BRAKE TEST ON TWENTY [illegible] [illegible]

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

In order to determine the effect of frequency on the operation of the motor a test was run with constant impressed e. m. f. of one hundred volts at twenty five cycles. The load was as before, varied over as wide a range as possible by means of the brake and readings were taken of the speed, current input, power input, and pressure of brake arm on the scales. The motor was also operated upon a variable voltage and constant current, the same observations as in the previous case being made.

BRAKE TEST ON DIRECT CURRENT

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

In order to make a comparison between alternating current and direct current operation we ran the motor on direct current at one hundred volts. We again made observations of the speed, current input, power input, and pressure of the brake arm on the scales the same as with the alternating current.

DISCUSSION OF CURVES

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

On curve sheet #1 are shown results obtained for sixty cycles at one hundred volts. The speed and torque curves are typical of those of those of the direct current series motor. The torque varies directly as the current input and the horsepower output also varies directly as the current input. The power factor decreases with an increase of load or armature input, attaining a minimum value of .723 at a speed of 645 r. p. m. The efficiency decreases staedily for an increase of load and is very low, - attaining a maximum value of only 62%.

On curve sheet #2 are shown the curves which were obtained at twenty five cycles and 100 volts. In this case the torque again increases diredtly with the current input but is somewhat greater for a given current than when operating on sixty cycles. The output increases nearly directly with the current and for a given current

value is about 30% higher than for the sixty cycle current. The speed for a given current is also much higher than when running on sixty cycles.

As might be expected the power factor is very much higher on twenty five cycles than on sixty cycles, due to the decrease of reactance both in the armature and the field circuits. In this case the power factor is practically constant for all current values, being equal to .98.

On curve sheet #3 are shown the characteristics when running on direct current. All of the characteristics are nearly the same as when running on alternating current. For a given value of current input the torque is higher than for alternating current of either twenty five or sixty cycles. The efficiency is also higher than for alternating current.

On curve sheets #4 and #5 are shown curves giving the relation of impressed voltage to speed,

torque, etc., at twenty five cycles. It is seen that the impressed voltage has little effect upon the torque in either case. The speed in both cases increases directly with the impressed voltage,- the increase in speed being greater on the sixty cycle than on the twenty five cycle for a given increase in voltage. The efficiency in both cases increases directly with the impressed voltage,- the efficiency being much higher for the twenty five cycle current.

The machine takes a very large current considering its output and heats up very rapidly when operated anywhere near full load. It was observed that this heating was most ptonounced when running on sixty cycle alternating current, while running on direct current the motor did not heat up nearly so rapidly. We did not make a heat run on the machine. It could be readily seen that it heated up excessively, as it became

so hot that one could not rest his hand on the frame.

The machine sparked somewhat for all loads on alternating current. On direct current the commutation was much better. The efficiency is rather low for a machine of this size. This is partly due to the large current taken by the machine and hence a large copper loss. The resistance of the circuit is about one tenth of an ohm so that when the motor is taking one hundred amperes the losses will be about one thousand watts or one and a third horsepower. The friction losses are also very high. This high friction loss is due partly to the brushes bearing on the commutator and amounts to nearly one horsepower. The brush construction is very poor, the brushholders being rigid and brushes bearing on the commutator in such a way as to have but little play.

DETERMINATION OF THE EFFECT
OF SPEED ON CORE LOSS

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

The following experiment was attempted in order to determine the effect of speed and frequency on the core loss. The scheme of connections is as shown in the figure. The alternating current motor was driven by an auxiliary direct current motor, direct connected. The efficiency of the direct current motor was determined by the stray power method for a number of speeds for which it was desired to test the alternating current motor for core loss. Alternating current at sixty cycles was then supplied to the main field of the alternating current motor and the current and power input were measured. The motor was driven at the various speeds and the field current was left constant. Readings of the watts input into the field of the motor and the direct current input to the d. c. motor were taken for each spe d.

The brushes were removed from the commuta-

tor during the test so that the total input minus the correction for efficiency, friction and copper loss is equal to the core loss. The friction loss for the different speeds was obtained by driving the alternating current motor at zero field excitation and measuring the input into the d. c. motor and correcting for efficiency. The copper losses in the a. c. motor were calculated. knowing the resistance of the field circuit.

The motor was tested for core loss at 90 amperes on sixty and twenty five cycles,- the speed being varied between 500 r. p. m. and 1200 r. p. m.

DISCUSSION ON CORE LOSS

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

It is a well known fact that the losses of a direct current armature or of a three phase armature are larger than those in the core of a transformer,- the volume, induction, and frequency being the same in each case. In the case of the direct current motor the magnetization is pro duced by the rotation of an iron body in a magnetic field, while in the transformer core there exists a local periodical variation of the field. In the single phase series motor both kinds of magnetization are combined. At standstill there is only a transformer action present but after starting the armature rotates in an alternating field and hence there are two different periodicities which have a bearing on the iron loss.

As seen from the curves the iron loss increases with the speed and as would be expected is higher on sixty cycles than on twenty five cycles. On sixty cycles the core loss ranges be-

tween five hundred and seven hundred fifty watts, the speed being varied from six hundred to twelve hundred revolutions per minute. On twenty five cycles the loss varied between two hundred forty and three hundred ten watts for the same speed variation. This core loss on sixty cycles is large for a machine of this size and accounts, to a large extent for the low efficiency.

EXPERIMENTAL DETERMINATION OF THE LOSSES DUE TO THE SHORT CIRCUIT CURRENT.

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

In order to determine the losses resulting from the current in the short circuited coil under the brush, the alternating current motor was driven by an auxiliary direct current motor, direct connected. The efficiency of the direct c current motor was determined by the stray power method. The motor was driven at one thousand revolutions per minute with the brushes raised from the commutator and the field not excited. The mechanical input in this case is equal to the friction and windage. The motor was then driven at one thousand revolutions per minute with the brushes down (bearing on the commutator) and the field not excited. The mechanical input in this case is equal to the total friction loss, including the brush friction.

With the brushes raised from the commutator the field of the alternating current motor was excited with different values of current and the

mechanical and electrical input measured. The input is equal to the mechanical loss plus the copper loss plus the core loss.

The brushes were then lowered onto the commutator and the mechanical and electrical input was again measured, the current as before being varied from zero to ninety amperes. This input is equal to the mechanical loss plus the copper loss plus core loss plus the short circuit loss.

As may be seen from the curves the short circuit loss increases rapidly with an increase of current after a certain value of load current has been reached. In this motor this loss is, however, much smaller than the loss due to the main line current and would lead one to suppose that the resistance of the leads in the armature coils is too high.

BRAKE TEST ON TWENTY FIVE CYCLES.

MOTOR #2.

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

This motor was designed to operare at two hundred volts on tenty five cycles. It is similar in all respects to the sixty cycle machine. The rating as to current or output was not placed on the motor but from the test results the output is about twenty horsepower at 850 r.p.m. A constant pressure of 200 volts was impressed upon the motor and the brake applied. Readings were taken of current, speed, power input, and pressure of the brake arm on the scales.

The desired voltage was obtained by stepping up from 100 volts to 1100 volts and then stepping down to 200 volts. Three fire K.W. transformers were used in parallel. The capacity of the alternator which furnished the power was only ten K.W. so that it was necessary to overload it considerably during the test. For this reason a heat run was not attempted as it was impossible for the alternator to carry the load for any

length of time.

The characteristics of this motor correspond very closely to those of large railway motors in present use. The efficiency is quite high,- reaching a maximum of 84%. The power factor is also high, decreasing directly with the current from .98 to .81. The torque varies directly with the current input and the speed curve is similar to that generally obtained with the series motor.

Very little sparking occured at the brushes under all conditions of load. The motor was operated at full load for only a short time. The temperature rise in any part of the machine during this time was inappreciable.

COMMUTATION AND RESISTANCE LEADS.

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

The difficulties which arise in the design of the alternating current series motor over that of the direct current series motor are due chiefly to the fact that the field is an alternating one. Because of this alternating field flux there is introduced the consideration of commutation and power factor. Any direct current series motor will operate on alternating current because the armature and field currents are in phase and both the armature and field flux are reversed at the same time.

The most series dif iculty encountered in the alternating current series motor is that of commutation. The effect of the alternating field flux upon the coil short circuited under the brush is to induce in it a high electromotive force, and hence a large current. The short circuited coil is the same as the secondary of a transformer of which the field is the primary.

The large current in the short circuited coil under the brush gives rise to two difficulties. First, it gives rise to excessive sparking at the brushes and a consequent overheating of the commutator, armature and brushes. Second, it causes the armature current to be out of phase with the field flux and hence the motor takes an increase of current.

The value of the e. m. f. induced in the short circuited coil varies directly as the number of turns per coil, the maximum value of the flux, and the frequency. It is, therefore, desirable to operate at a low frequency and to use as few armature turns per section as possible. But with these precautions the short circuit currents are still too large for good commutation.

Various methods have been introduced for decreasing the short circuit current. Of these, the most successful, and the most generally used,

is that of placing resistance leads in each coil between adjacent commutator segments. The leads usually consist of German Silver wire placed in each coil and so arranged as to be in parallel with respect to the main line current, but in series with respect to the short circuit current.

By this method the short circuit current may be decreased as much as desired. With an increase of the resistance leads the resistance to the main line current is also increased, so that, while the commutation has been improved upon, the copper loss in the armature has been increased. In order to obtain the most efficient results it is necessary to have the short circuit loss and the main line current loss equal, and the resistance leads are usually such as to produce this effect. Although the resistance leads are objectionable, due to the loss of power which occurs there, it must be remembered that without them

the short circuit current would be very large and hence the combined short circuit and armature loss would be considerably greater than without them.

In American practice the resistance leads have been used almost exclusively. In European practice many methods have been adopted for decreasing the sparking both at starting and under running conditions. All of these methods are similar in this respect that they tend to induce a second transformer e. m. f. into the short circuit coil so as to oppose the first, and hence neutralize it entirely. This is accomplished by inserting extra coils in the circuit, which have a transformer effect upon the short circuited coil. Such a construction, however, requires certain complications which are not very desirable in a large commercial machine.

In the Westinghouse motors built for the locomotives of the New York, New Haven and Hartford Railroad the resistance leads are used to prevent

sparking at the brushes. The armature is completely closed upon itself and the resistance leads are tapped to the armature winding at the end of each turn, and are then joined to the commutator. In this construction only one turn per armature section is used, with the result that the transformer e. m. f. in the short circuited coil is comparatively low. The resistance leads are, furthermore, placed so as to be non-inductive so that the short circuit current is approximately in time phase with the transformer e. m. f. in the armature coil, or in time quadrature with the main armature current. The result of this is that the armature current and the field flux arenot out of phase due to the short circuit current.

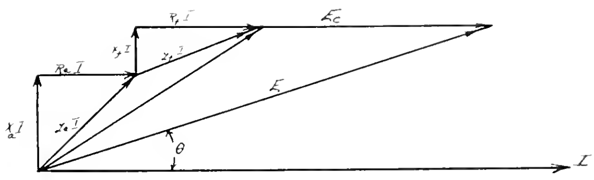
The resistance leads are covered with insulating material similar to that used on the main armature winding and are placed in slots beneath the main armature winding.

DISCUSSION ON POWER FACTOR AND SIZE OF MOTOR

A STUDY OF THE ALTERNATING CURRENT SERIES MOTOR

Due to the alternating current in the a. c. series motor circuit there is to be considered the reactance of the field and armature circuit in addition to the resistance. Due to the naturally high inductance of the field and armature circuit there is introduced a considerable angle of lag of the current behind the impressed e. m. f. The cosine of the angle between the two quantities being the power factor.

The conditions upon which the power factor depend may be best understood by means of the clock diagram as given below.



Z_aI is the impedance of the armature and Z_fI is the impedance of the field circuit. E_c is the counter e. m. f. generated in the armature andis practically in phase opposition to the current. From the diagram it is se n that, in order to obtain good power factor it is necessary to have the impedance of the field and armature circuit as small as possible in comparison with the counter e. m. f.

The inductance of the armature circuit is. naturally quite high and in order to reduce this it is necessary to insert a set of coils whose magnetomotive force is opposite to that of the armature coils, and hence neutralize the flux surrounding the armature conductors. This is accomplished by placing in tne pole faces a number of coils parallel to the armature inductors and carrying a current in a direction such that the magnetomotive fòrce opposes that of the conductors in the armature.

The flux set up by these coils is at right angles to the main field flux. These coils may be connected either in series wiht the armature or they may be short circuited upon themselves. In the f former case the compensation is called conductive and in the latter case inductive or transformer compensation. With the transformer compensation the armature flux is neutralized completely. With the compensating coils connected in series with the armature the compensation may be varied. Due to the air gap between the pole face and the armature there is some leakage so that compensation is never quite complete and a small reactance is present in the armature and compensating coil circuit.

In order to introduce a low value of field reactance it is necessary to produce the desired flux with as few turns on the field as possible. It is, therefore necessary to work at a low flux density or to use a large number of poles with

few turns per pole. For a certain field current the flux varies as the first power and the reactance as the second power of the number of turns. The advantage in using a large number of poles lies in the fact that the magnetomotive force for producing the desired flux is distributed throughout a few turns, which results in a smaller reactance than if the flux were produced by the same number of turns but not distributed.

In order to have the counter e. m. f. as large as possible for a given speed and flux it is necessary to have a large number of turns on the armature. In other words the armature circuit should be magnetically strong in comparison with the field circuit. As a rough approximation it may be stated that at synchronous speed the tangent of the angle of lag (of which the cosine is the power factor) is equal to the ratio of the effective field to armature turns and it decreases

inversely with an increase of speed. The power factor can, therefore, be rendered quite high by using a small ratio of field turns to armature turns and operating the machine at a speed which is high in comparison with synchronous speed.

Since the reactance of the field and armature circuit is directly proportional to the frequency, other things being constant, it is obvious that the reactance will be decreased and the power factor increased by decreasing the frequency.

Due to the lag of the current behind the e. m. f. the apparent input into an alternating current motor may be divided into two components at right angles to each other. One is the energy and the other is the inductive component. The energy component represents the useful input into the motor, and therefore, the output at the shaft plus the losses. Since the power factor is only a ratio of two quantities, that is, the energy

component to the total apparent input, it gives but little information as to the actual operation of the motor. The important consideration is the relative magnitude of the energy and inductive components. This may be determined when the power factor and the apparent input is known.

A high power factor does not always mean the most satisfactory operation of the motor and the effects which are ordinarily attributed to a low power factor are really due to a large inductive component. If the value of the inductive component is left constant for any given input and the power factor is raised by increasing the energy component the conditions will be worse than before. Again consider two motors which for the same output have the same inductive component but the efficiency of the first is greater than that of the second, then it follows that the energy component of the first must be less than that of

the second. In this case the motor with the higher power factor is the poorer of the two since it has the same inductive component but a lower lower efficiency than the machine witht the low power factor.

In the series machine the inductive component is proportional to the current and since the same current is required to produce the same torque, no matter whether the machine is just starting or running at full speed, it will be evident that the inductive component is the same for any given torque. At starting, however, the power delivered and hence the energy component is very small so that the power factor will necessarily be low while at full speed the power delivered and hence the energy component will be large so that the power factor will be high. Since the power factor at full load is usually quite high it follows that the inductive component must be

comparatively small. Since for a given torque the inductive component is the same in starting as under load conditions it follows that for a motor with a high efficiency the power factor in starting will be low since the energy component is entirely due to the losses. On the other hand a low efficiency motor will on starting have a high power factor since in this case the losses and hence the energy component will be large.

The torque developed by the motor is proportional to the current and a given torque may be developed by means of a wattless current as well as an energy current. It is therefor desirable to produce the required torque with as little expenditure of energy as possible. Since the inductive component is always present it is desirable at starting to have a low power factor, hence a small loss, and produce the torque by means of the wattless current. From the above discussionit wi l

be seen that as far as the operation of the motor is concerned a high power factor is not necessarily desirable under all operating conditions.

From the foregoing discussion it will be apparent that the alternating current motor for a given output will be large than the direct current motor. The field core being worked at a lower flux density than for a direct current motor will require a larger cross-sectional area, or there will be a greater number of poles than in the direct current machine. Considerable room is also required for the compensating coils. In order to reduce sparking the commutator will require a larger number of segments than in the direct current machine. In order to develop a high counter e. m. f. for a fixed speed and field flux it will be necessary to have a large number of armature conductors and hence the size of thearmature will be increased over that of the direct current motor.